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Quantitative depth for a phantom surface can be based on cyclopean occlusion cues alone

Barbara Gillam [a,*], Ken Nakayama [b]

[a] *School of Psychology, University of New South Wales, Sydney 2052, NSW, Australia*
[b] *Department of Psychology, Harvard University, William James Hall, 33 Kirkland St., Cambridge, MA 02138, USA*

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Abstract

Liu, L., Stevenson, S.B., and Schor, C.M. (1994, Nature, 367, 66–669) reported quantitative stereoscopic depth in a phantom rectangle which appeared to lack conventional matching elements. Later, Gillam, B.J. (1995, Nature, 373, 202–203) and Liu, L., Stevenson, S.B., and Schor, C.M. (1995, Nature, 373, 203) and Liu, L., Stevenson, S.B., and Schor, C.M. (1997, Vision Research, 37(5), 633–644) indicated that the varying depth of the phantom rectangle could be based on stereoscopic matching. To remove the contaminating effects of conventional stereopsis from the Liu et al. (1994) original example, we presented a pair of parallel vertical lines to each eye where there is a central gap in the right line for the left eye's view and in the left line for the right eye's view. Observers saw a phantom rectangle bounded by subjective contours whose depth increased with the thickness of the lines. We attribute the quantitative variation of depth to a purely cyclopean (binocular) process sensitive to the pattern of contour presence and absence in the two eye's view.

Keywords: Binocular; Depth; Occlusion; Cyclopean; Matching

1. Introduction

Liu, Stevenson and Schor (1994) presented a stereogram (Fig. 1(a)) which when fused is seen as a black rectangle with a phantom white rectangle in front of it. The apparent depth of the phantom rectangle varies with the thickness of the vertical bars. In their first presentation of this figure, they attributed the phantom surface to occlusion cues given by the presence of the vertical bar in the left eye's view but not in the right eye's view and vice versa. Although Nakayama and Shimojo (1990) had demonstrated that a phantom occluding surface can be generated by unpaired points and had shown that an unpaired element can vary quantitatively in depth with respect to a binocular surface, the paper by Liu et al. (1994) was important as the first measurement of the depth seen in a phantom surface generated by occlusion cues, and the first demonstration that it can vary quantitatively with respect to a binocular surface. Subsequent studies, however, have questioned whether the size of the monocular occluded region is the cause of the metrical variations in perceived depth.

Gillam (1995) argued that although there were no matching vertical contours in the Liu et al. stereogram, matching horizontal contours with the same polarity in the two eye's views were present and could account for the depth effect by normal stereoscopic matching (Fig. 1(b)). Liu et al. (Liu, Stevenson & Schor, 1995, 1997) countered this argument by pointing out that the horizontal contours in Fig. 1(a) have different polarity at their terminations in the two eyes whereas the horizontal contours in Fig. 1(b) have the same polarity, thus seeming to disagree with Gillam's criticism. Yet, more broadly they have agreed with Gillam's point by giving serious consideration to possibly unsuspected conventional stereoscopic mechanisms that could explain their original results[1].

* Corresponding author. Fax: +61 2 93853641; e-mail: B.Gillam@unsw.edu.au.

[1] Fig. 1c shows however that the stereoscopic depth response to horizontal contours in normal stereopsis does not require that their terminations have the same polarity so long as the same polarity exists along the length of the lines. We have confirmed this observation with five naive subjects who reported the inner lines as nearer in the crossed case and further in the uncrossed case.

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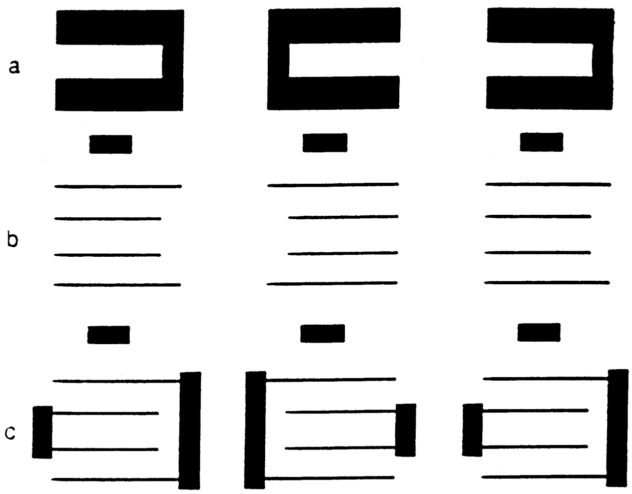

Fig. 1. (a) Stereogram from (Liu et al., 1994) which is perceived as a white 'phantom' rectangle in front of a large black rectangle; (b) stereogram from (Gillam, 1995) composed of horizontal lines in the positions of the horizontal contours of the Liu et al. stereogram. The central pair is perceived in front of the outer pair of lines.(c) the Gillam stereogram with black rectangles positioned to abolish the identical luminance polarity at the ends of the horizontal lines. The depth effect as in (b) is still perceived. (see footnote 1). Crossed fusers should use the left pair and uncrossed fusers should use the right pair in each stereogram.

In their initial reply to Gillam, Liu et al. (1995) proposed a new explanation of their effect; a hitherto unsuspected process by which corners with different polarity in the two eyes can be matched stereoscopically. More recently, and relying on careful and extensive modeling efforts (Liu et al., 1997), they have taken this argument a step further, showing that convolving the images of their original stereogram (Fig. 1(a)) with Gabor filters at oblique orientations produces corner configurations in the left and right eye views which can be matched by normal stereoscopic processes; i.e. it produces similar response patterns in the two eyes whose disparity will vary to explain the depth perceived[2]. In this new account, occlusion geometry relying on the width of unpaired images is relegated to a possible minor role; that of extrapolating surfaces between the matched corner details in the filtered images.

Thus to summarize the topic so far: Liu et al. (1994) made the interesting and important claim to have found quantitative variation in depth of a phantom surface without binocular correspondence. Gillam (1995) questioned this by raising the possibility of the matching of horizontal contours in their original display. Liu et al. (1995; 1997), while disagreeing with the particulars of Gillam (1995), acknowledged that the variation in metrical depth could have been mediated by conventional stereopsis.

In reviewing the Liu et al. (1994) paper, it is now apparent that their original experiment contained two potential cues for depth: (1) conventional stereoscopic cues; (2) stereocopic occlusion cues. Subsequent papers have focused on the contaminating effects of conventional stereoscopic cues, thus seeming to dismiss the possibility that there was any contribution from occlusion cues alone. Yet, the possibility remains.

In the present paper we present quantitative evidence for a phantom object in depth which is similar to the original Liu et al. figure but which excludes any form of conventional stereoscopic matching. Our stereogram (see Fig. 2) is based on a simpler stimulus, modified to create a central gap in the right line for the left eye's view and in the left line for the right eye's view. Unlike the Liu et al. stereogram, this stereogram has no horizontal contours and importantly no corners in the contralateral eye which could be matched to the ends of the monocular gaps or provide the basis of a match after selective filtering of the images. A phantom rectangle is nevertheless seen in depth in front of the figure, occluding part of the right line for the left eye and part of the left line for the right eye. The phantom rectangle thus 'accounts for' the gaps. Fig. 3 illustrates the geometry of occlusion in the present case. It can be seen that the minimum depth of the occluding surface depends on the thickness of the lines. The thicker the lines the further in front of the lines a surface must be to occlude a segment of the line for one eye and not the other. This constraint specifies only a minimum depth not a maximum. In Experiment 1, we measure the depth effect and show that it varies quantitatively with the thickness of the lines.

2. Experiment 1

2.1. Method

The stimuli are illustrated in Fig. 2. They consisted of vertical lines whose thickness varied from 0.225 to 1.125 mm, viewed from a distance of one meter (visual angle thickness ranged from 0.77 to 3.87 min.arc). The height of the lines was 43 mm and their separation was 27 mm. A central gap of 9 mm was inserted in the left line for the left eye's view and in the right line for the right eye's view. The two views were presented in fast alternation (120 Hz) on the computer screen of an SC INDY and viewed through Liquid Crystal Shutter Glasses so that each eye saw only one pair of lines at a frequency of 60 Hz. Subjects were shown the binocular display and asked what they saw. If they reported the phantom rectangle (all did) they were asked to set a

[2] We note in proof a new article by Liu et al. (1998) in which they produce evidence contradicting their 1997 explanation of the phantom surface based on Gabor filtering of the images.

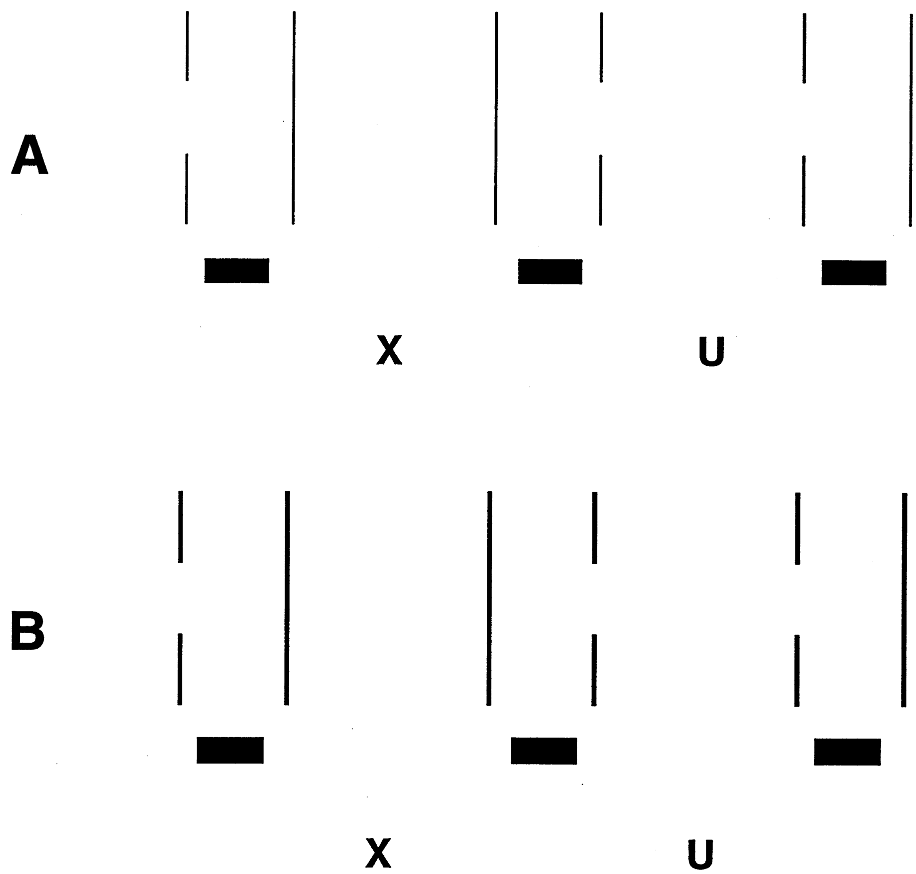

Fig. 2. New stereograms which when fused reveal a phantom white rectangle in front of vertical black bars. The apparent depth of the rectangle appears to increase with the thickness of the bars. Bars in (b) are twice those of (a).

binocular probe of variable disparity so that it appeared to be at the same depth as the rectangle. The probe was a dot 0.45 × 0.46 mm placed 3cm beneath the lines and centered on them. Disparity could be varied by moving the computer mouse. Each line thickness was presented four times to each subject in random order. Four subjects were used of whom two, PW and DA, were completely naive with respect to the rationale of the experiment.

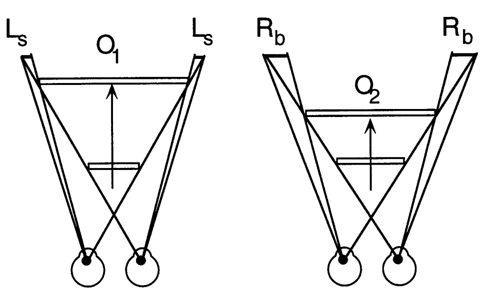

Fig. 3. Top view of the physical situation which could have given rise to the binocular images shown in Fig. 2 taken at the level of the 'gaps'. The left picture depicts the case for thin vertical bars as in Fig. 2(A). The right picture depicts the case for the thicker vertical bars as in Fig. 2(B). Ls and Rs and Lb and Rb represent the small and large left and right bars respectively. Note that the objects O1 and O2 are consistent with the binocular image in that only the left eye can see the left bar and only the right eye can see the right bar. Note that the smallest possible depth difference between the object and the bar is less for the thin bar case (A). Note also that smaller and closer phantom objects can also satisfy constraints imposed by the binocular images.

2.2. Results

The results are shown in Fig. 4. All subjects set the probe at a depth which increased with line thickness. The depth in each case was however considerably greater than the minimum specified by the thickness constraint (shown by the dotted line) and the matched depth varied between subjects.

2.3. Discussion

The quantitative variation of depth in the phantom rectangle reported here cannot be explained by the presence of physically matching elements in the two eye's views since neither its vertical edges, its horizontal edges nor its corners are represented in both monocular images. Convolving the monocular images with Gabor filters of any orientation will not produce a match for the ends of the monocular gap in the other eye's view which could provide the basis of a varying depth signal since the output of any such convolution for any filter

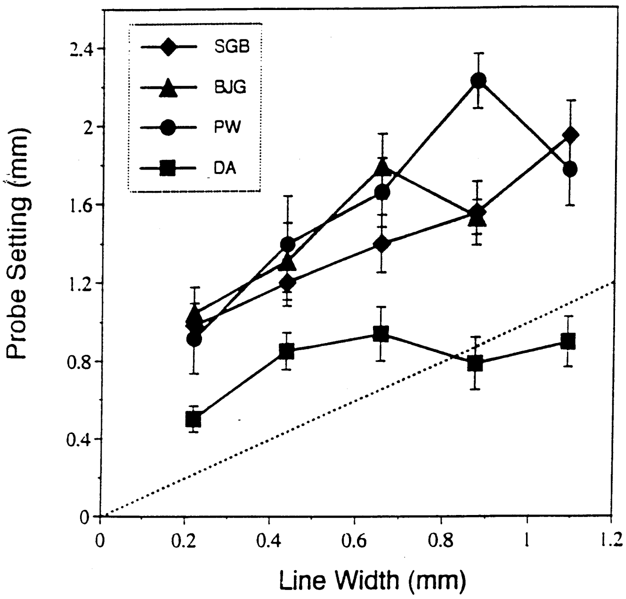

Fig. 4. Mean stereo probe settings for four subjects as a function of bar width using stereograms like those shown in Fig. 2 (see text for details). The minimum depth which would satisfy the constraints depicted in Fig. 3 is shown by a dotted line.

orientation will not vary along the length of the continuous line. For this reason, our experiment supports the original Liu et al. (1994) claim that quantitative depth can occur without binocular matching. Yet, because the perceived depth is not as accurate as that for conventional stereopsis it reinforces the view that the original Liu et al. configuration is likely to have had binocular cues as well. On the basis of our elimination of the alternative possibilities applying to their figure, we suggest that the phantom rectangle, seen in Fig. 2, like previous qualitative demonstrations of Nakayama and Shimojo (1990) and Anderson (1994), is evidence for the ability of the visual system to perceive a subjective surface based solely on a pattern of presence and absence of details in the two eyes consistent with occlusion by a nearer surface. Our new data shows that this process can produce quantitative depth.

The fusion of a single continuous line in one eye and a single line in the other eye with a central gap produces the suggestion of occlusion at the gap but both left and right lines of the configuration are necessary to produce the phantom surface. This indicates cooperation across some distance among several indicators of occlusion which are consistent with the same surface. Thus, the surface recovery process has both local and non-local aspects.

If the ‘X’ pair of the left and right images in Fig. 2 are viewed with uncrossed fusion and the ‘U’ pair are viewed with crossed fusion so that part of the left line is missing for the left eye and vice versa for the right eye, no surface is reported. This binocular arrangement is not consistent with an occluding surface. Only viewing through an aperture could produce the situation in which part of the left line is missing for the left eye and part of the right line for the right eye. This would probably involve seeing phantom regions on the outside of the lines where the gaps are. There is little sense of this. Five naive subjects, all of whom reported the phantom rectangle in front in the crossed case, reported that they did not perceive such a surface in the uncrossed case and did not report seeing an aperture[3]. It should be noted that perceiving the occluding surface in the crossed case is supported by the fact that the occlusion directions indicated at the two gaps are consistent with a single surface as indicated above. The perception of an aperture would involve perceiving occlusions coming from opposite directions which would each have little stimulus support. Our stereogram behaves differently in this respect from that of Liu et al. (1994). Their subjects did perceive a surface behind in the uncrossed case which was just as metric in depth as the surface in front. We would attribute this to the regular stereoscopic disparities present in their stereogram. The fact that our stereogram does not support perception of a surface behind in the uncrossed case reflects its lack of regular stereoscopic cues.

Previous studies (Gregory & Harris, 1974) have shown that disparate subjective contours in the two eyes may produce apparently occluding surfaces in depth. The phantom rectangle on the other hand belongs to a class of subjective contours which are based on occlusion cues which only exist by comparison between the two eye’s views. These phenomena can be regarded as examples of ‘cyclopean’ occlusion.

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[3] It should be noted that author KN, who is experienced at observing surface patterns in stereograms can see this case fleetingly, two vertical apertures through which is seen a white horizontal bar completing behind.